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Geometrical Variation from Selective Laser Heat Treatment of Boron Steels

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Abstract

Selective laser heat treatment is used to enhance material properties in high strength steels and finds wide range of applications in the automotive industry. However, the manufactured components also become sensitive to variation affecting functionality, esthetics, and performance of the final product. In this paper, selective laser heat treatment of boron steels is analyzed with emphasis on geometrical variation. Different manufacturing strategies are tested by varying heating direction sequence and heat treatment pattern and their influence on springback is investigated. The results indicate their significant contribution to geometrical variation and the need to consider them in various stages of the geometry assurance process.

Keywords: selective laser heat treatment; geometrical assurance; robust design

1. Introduction

The automotive industry is largely driven by stringent emission norms to fulfil sustainability requirements. Continuous efforts are made to reduce vehicle weight without compromising on the crashworthiness of the vehicles. Of the material alternatives available, ultra high strength steels such as boron steels have been at the forefront to fulfil this criteria. Boron steels are used in vehicle body for components such as A-pillar, B-pillar, roof rail, rocker rail to name a few, due to its strength properties [1]. SAAB Automobile AB were the first to use hardened boron steels in their vehicle body in 1984 [2]. Since then, its application in vehicle industry has extensively increased. However, formability issues of boron steels poses a challenge in further utilizing its potential. Therefore, novel manufacturing processes capable of overcoming such issues and producing light weight solutions are necessary.

Tailored heat treated blanks technology (THTB) is one such novel method that enhances formability and strength of the material through local modification of material properties [3]. Unlike conventional heat treatment methods where the entire metal blank is heated before stamping, this process involves locally heating selective areas of the metal blank. The local modification in material properties improves formability and imparts strength into the material. This selective (local) heat treatment can be performed by means of laser irradiation, electromagnetic induction, or through heat conduction. Specifically, laser source mounted on a robot provides additional flexibility in processing of complex geometry shapes. Thus, optimal process parameters and selective areas for local heating can be identified to get the desired output. It also gives considerable freedom to engineers in designing complex geometry components.

Several researchers have investigated the outcome of selective laser heat treatment process with respect to formability. Vollertsen et al. [4] applied local laser heat treatment for aluminium alloys using CO_2 laser and showed that drawability could be increased. This was further tested and proven by Hofmann [5]. The effectiveness of laser irradiation in selective heat treatment process could be further improved using Nd:YAG laser was shown by Geiger et al. [6]. Merklin et al. [7] studied multi-path heating strategy for aluminium blanks and Hung et al. [8] considered heat treatment layouts to demonstrate impact of hardening. Neugebauer et al. [9] used local laser heat treatment to demonstrate improvement in formability in ultra high strength steels as well. Conrads et al. [10] showed the influence of local laser heat treatment on crash behavior of advanced high strength manganese steels by

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imparting strength into the material. Heat treatment patterns were used to control deformation path and the crash behavior. Asnafi et al. [11] performed selective laser heat treatment on boron steels and tested different strategies to improve both formability and strength of the material. Significant improvement in formability as well as a rise in the hardness at the heat treated areas were shown.

While the material properties are improved from the selective laser heat treatment process, it also results in undesired stresses and distorts the material. Various processing parameters such as laser power, laser heating direction, choice of heat treatment pattern, laser heating speed or their combined effect leads to variation. The positioning system, fixtures, and most important of all, design robustness are significant contributors as well. Here, robust design is defined as a design insensitive to variation such that the performance characteristics are unaffected by variation [12]. Geometrical variation, even if minimal at part level, propagates through the assembly process and often amplifies in an assembled product. It affects functionality, esthetics, and performance of the product. Crash behavior which is an essential requirement for structural components in vehicle body can get compromised. Hence, minimizing effect of such variation becomes necessary.

1.1. Scope of the paper

This paper is aimed at understanding geometrical variation from selective laser heat treatment of boron steels and how it affects subsequent stamping process, a domain where information remains scarce and requires further exploration. Influence of laser heating direction and heat treatment pattern is focused upon. The knowledge generated will serve in minimizing effects of geometrical variation through geometry assurance process. The paper is structured with section 2 providing background on boron steels and the selective laser heat treatment process. In section 3, an overview of geometrical variation and robust design is provided. Case study performed is described in section 4 and its outcome is discussed in section 5. Section 6 summarizes and concludes the paper.

2. Background on Boron Steels and Selective Laser Heat Treatment Process

In this section, the background on boron steels with respect to its hardenability mechanism is given. It is followed by detailed explanation of the selective laser heat treatment process.

2.1. Boron steels

Boron steels are commonly used in the automotive industry as it offers economical and high weight-saving possibilities. Boron steels up to 40% of total vehicle weight have been used to improve crashworthiness as well as achieve substantial weight reduction [13]. Presence of boron as an alloying element improves hardenability in steels. Boron content in the range of 0.001% weight to 0.003% weight provides maximum hardenability [14]. Due to this high hardness, boron steels have good wear resistance properties. However, this affects formability of the steel and wears the stamping tool as well. In order to overcome this, boron steel parts are produced by hot stamping process. Hot stamping process consists of heating the metal blank in a furnace to elevated temperatures. The heating process softens the metal as the microstructure transforms to austenite phase. The metal blank is then transferred to the stamping tool. The softened boron steel blank is simultaneously formed to desired shape as well as quenched rapidly due to its contact with the stamping tool. Presence of boron delays transformation to other phases such as bainite, ferrite, and pearlite microstructures which are much softer [15]. Hence, the microstructure transforms to martensite as a result of rapid quenching and stamping thereby increasing the hardness of the material. The as-received yield strength in the range of 300-550 MPa can be increased to 1000-1300 MPa from the heat treatment process [15].

2.2. Selective laser heat treatment process

Selective laser heat treatment is a process of heating along the pre-defined pattern instead of heating the entire metal blank. The process utilizes lesser energy in comparison to furnace method as only desired areas are heated. Input energy can be efficiently utilized as laser power can be controlled. This process can be relatively quick as it can be automated as well. Quench medium such as oil and water can be avoided as it can be self-quenched under room temperature conditions and thereby making the process more environmental friendly.

The source and means of laser generation has progressed over the years, from lamp pumped and gas lasers to high power diode lasers. Laser types such as Nd:YAG, CO_2, diode lasers are used for various applications. Nd:YAG lasers are preferred over CO_2 lasers due to shorter wavelength as they are absorbed faster. This also avoids coating of surfaces to enhance absorptivity [16]. Nd:YAG and diode lasers can be coupled with fiber optic cables for increased laser intensity. Intensity in the range of 10^3-10^4 (W/cm^2) with beam to surface interaction time of 0.01-0.1 second is sufficient enough for transformation hardening [17]. The setup consists of laser source mounted on a robot (Fig. 1). The selective areas are chosen in the form of a pattern. The pattern constitutes of multiple heat treatment areas as shown in Fig. 1. These pre-determined selective areas are then laser heated. The metal blank is positioned using clamps (C) (Fig. 2). Laser beam irradiates the surface and heats up the area sufficient enough to transform to austenite microstructure.

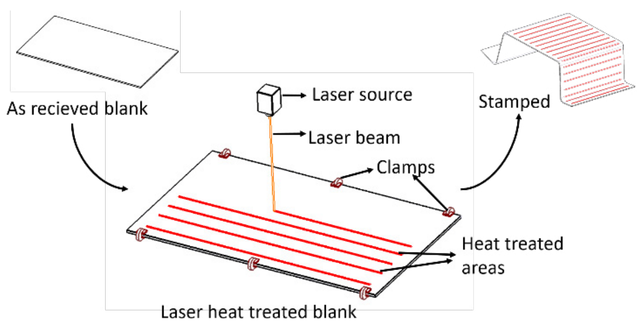


Fig. 1. Selective laser heat treatment process chain

In case of boron steels, austenite microstructure begins to form on reaching temperature known as Ac_1 (≈750°C) and is completely transformed to austenite on reaching temperature known as Ac_3 (≈880°C). Heat treated area expands due to heating and tensile stresses are generated. The surrounding cold bulk region (base metal) acts as a heat sink suppressing the expansion and induces compressive stresses onto the heat treated area as depicted by the arrows (Fig. 2a).

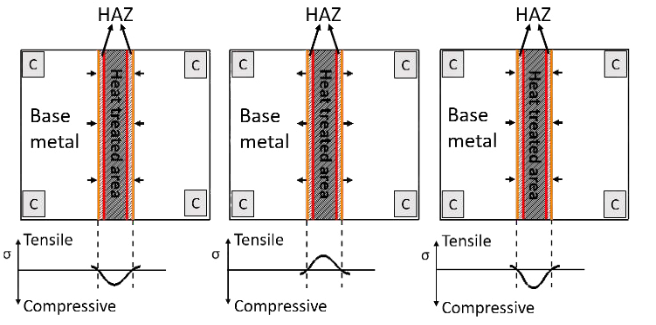


Fig. 2. Selective laser heat treatment process mechanism

Performed under room temperature conditions, the heat treated area begins to rapidly quench. The area starts to contract but is opposed by the surrounding cold bulk region and induces tensile stress onto it (Fig. 2b). The microstructure transforms to martensitic phase at the end of quenching process. The austenite to martensite transformation leads to volumetric expansion [18]. The surrounding cold bulk region opposes this volumetric expansion and induces compressive stresses (Fig. 2c). This residual compressive stress improves fatigue life of the part. Heat affected zones (HAZ) are also formed alongside the heat treated area as well as across the thickness. The microstructural properties of HAZ differs from the heat treated area and the base metal. It acts as a transition zone. In boron steels, austenite gets retained due to rapid quenching as they do not fully transform to martensite. The amount of retained austenite present depends on the carbon content in the material as well. The magnitude of stresses and thereby the magnitude of springback generated is also dependent on the penetration of the laser along the thickness of the material. This in turn dependent on laser power and laser heating speed.

3. Geometrical variation and robust design

In this section, the nature of geometrical variation arising from selective laser heat treatment process is categorized and further classified based on the source of variation. The geometry assurance process and the concept of robust design are discussed in detail.

3.1. Geometrical variation

Geometrical variation arising from selective laser heat treatment can be categorized with respect to shape and size [19]. Shape variation occurs due to stresses generated in the process. When the stresses generated exceed the yield strength of the material, it undergoes plastic deformation. The surrounding bulk region opposes such effect thereby distorting the material [20]. The material also buckles if the heating relaxes inbuilt stress from the previous process. Phase transformation from austenite to martensite causes volumetric expansion and alters the size of the material. Residual stresses are formed from the above processes. They impact subsequent stamping process, assembly process and so on. Positioning system of fixtures and clamping tools also propagate variation.

Hence, geometrical variation can be classified into part, assembly and design concept variation [21]. The shape and size variation described above is associated to part variation. Variation arising from fixtures and clamping tools can be regarded as assembly variation. Both part and assembly level variation increases when the design is sensitive to such variation. A robust design concept that is insensitive to variation suppresses variation at other levels.

3.2. Robust design in geometry assurance

The geometry assurance process consists of a set of activities aimed at minimizing the effect of variation. The activities are divided within phases namely, the concept phase, the verification phase, and the production phase [22]. Robust design is an activity carried out in the concept phase. It consists of series of activities such as allocation of robust locating schemes, variation simulation and tolerance allocation.

In robust geometry design, manufacturing variation is considered as main source of variation amongst others. The design can be made robust by having a suitable locating scheme and the locating points are chosen in such a way that it minimizes variation propagation.

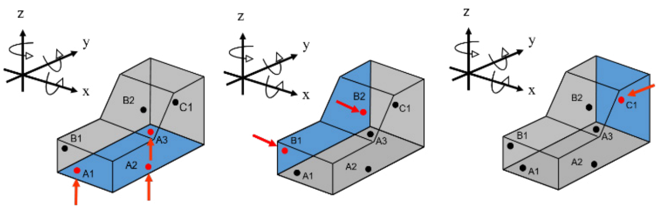


Fig. 3. 3-2-1 locating scheme

A 3-2-1 locating scheme is commonly used to locate rigid parts to minimize variation (Fig. 3) [23]. A1, A2, A3 are primary points locking three degrees of freedom, translation in Z-direction (TZ) and rotation in X-direction (RX) and Y-direction (RY). B1 and B2 are secondary points that lock two degrees of freedom, translation along X-direction (TX) and rotation in Z-direction (RZ). C1 is a tertiary point that locks the remaining one degree of freedom, translation in Y-direction (TY). Extra support points can also be used in case of non-rigid parts such as sheet metal parts. The main rule is to re-use the same locating system at all stages, i.e. at part manufacturing, assembly and inspection [24]. Once the robustness controlled by locators are addressed, tolerances can be considered to control variation at on assembly level. In order to consider tolerances for parts made from laser heat treatment process, understanding of part variation from the process is necessary. It will then allow to analyze different heat treatment patterns and heating directions for a design concept, assign tolerances that fulfil functional aspects of the final product.

4. Case study

In this case study, selective laser heat treatment of boron steel was carried out with different heating direction sequence and heat treatment pattern strategies. Three heating direction sequence strategies have been tested on two heat treatment patterns. The blanks were laser heat treated based on the above mentioned strategies as the first step. In the second step, 3D laser scanning of these heat treated blanks were carried out to capture the complex nature of blank deformation in detail [25]. In the next step, the same heat treated blanks were subjected to stamping followed by 3D laser scanning. A 3-2-1 locating scheme was used for positioning during 3D laser scanning. The 3D scanned models of heat treated blanks were compared with that of an untreated blank as a nominal part to analyze geometrical variation as a final step. The 3D scanned models of stamped parts were examined for the nature of springback.

Geometrical variation analysis with nominal part was carried out using RD&T software. RD&T is a software for Robust Design and Tolerance Analysis equipped with multiple functions for analysis at different stages of design process. Stability Analysis for analyzing design robustness, Variation Analysis for analyzing design variation, Contribution Analysis for assessing points and tolerances contributing to measure variation are some of its functions [26]. Details of the case study is described in the sub sections below.

4.1. Setup

A fibre fed diode laser with square beam of 6mm was used for the tests. Laser power of 670 W and laser heating speed of 22 mm/sec were kept constant for all the tests. Maximum temperature of 950°C was achieved. 1mm thick boron steel blanks named Boloc steel grade 02 was used in the case studies [27]. The material details are provided in tables 1-3.

Table 1. Material composition of Boloc 02 steels [27]

C% Min-max	Si% min-max	Mn % min-max	P % max	S % max	Cr % min-max	B % min-max
0.2-0.25	0.2-0.35	1.00-1.30	0.030	0.01	0.14-0.26	0.0015-0.005

Table 2. Hardening in different cooling media [27]

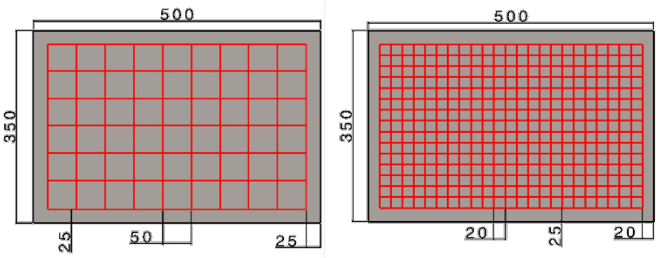
Condition	Cooling media	Tensile strength Rm N/mm2 ca.	Elongation A80 % ca.	Hardness HV ca.
Hardened	Oil	1370	8	450
Hardened	Water	1590	6	520

Table 3. Mechanical Properties [27]

Condition	Yield strength R_e N/mm^2 ca.	Tensile strength R_m N/mm^2 ca.	Elongation $A_{80\,\%}$ ca.	Hardness HV, ca.
Annealed	340	480	28	140

4.2. Heat Treatment pattern

In order to understand the influence of heat treatment pattern on variation, square grid pattern of two different dimensions were chosen for the tests. Pattern A with grid dimensions 50x50 mm (Fig. 4a) and Pattern B with grid dimensions 20x20 mm (Fig. 4b) were implemented. Pattern B covers larger blank area than pattern A due to its smaller grid dimensions implying more heat treated areas.



(a) (b)

Fig. 4. (a) Heat treatment pattern A (b) Heat treatment pattern B

4.3. Heating direction sequence

The above mentioned heat treatment patterns were applied on the blank by varying the heating direction sequence. Three different heating direction sequence (HS) strategies were tested.

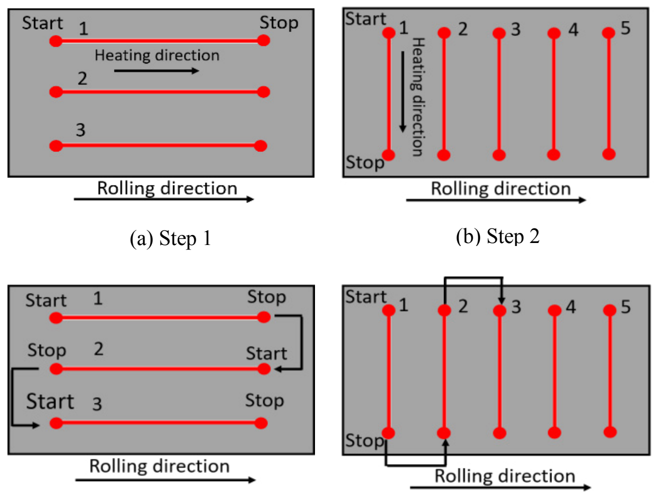
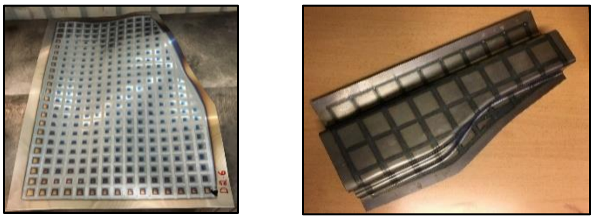


Fig. 5. Heating direction sequence strategies

In HS1, step 1 (Fig. 5a) was carried out first followed by step 2 (Fig. 5b). Laser heating begins from start position of area 1 and ends in stop position of area 1. The robot then re-positions to start position in area 2 and laser heating process continues. In HS2, the sequence was reversed. Step 2 (Fig. 5b) was carried out first followed by step 1 (Fig. 5a). In HS 3, start and stop positions were altered as shown in Fig. 5c and Fig. 5d. Initial try outs of selective laser heat treatment and stamping were carried out which lead to cracks. As a solution, the blanks were trimmed first and then laser heat treated (Fig. 6a). The heat treatment pattern was adapted according to the trimmed blank dimensions. Stamping binder pressure was set to 90 bar to avoid cracks. The heat treated blanks were stamped to desired shape (Fig. 6b). The laser heat treatment processing time of blanks for HS1 and HS2 in case of Pattern A was 340 seconds and Pattern B was 795 seconds respectively. While, the laser heat treatment processing time for HS3 in case of Pattern A and Pattern B was 295 seconds and 674 seconds respectively.



(a) Heat treated blank – Pattern B (b) Stamped part – Pattern A

Fig. 6. Heat treated blank and stamped part from test case

5. Results

The 3D scanned data of heat treated blanks were investigated for geometrical variation by comparing with a nominal blank geometry using RD&T. Variation across all the mesh nodes in the 3D scanned data of heat treated blanks was computed and the root mean square (RMS) variation was calculated. RMS variation captures the sensitivity of the variation, see [28]. This RMS variation from the heat treated blanks was then compared with springback after the same blanks were stamped. It was observed that heating direction sequence and heat treatment pattern affected the nature of variation at blank level. This in turn had influence on stamped parts and was evident from the nature of springback.

5.1. Heat treatment pattern A

The mean variation at blank level and the corresponding springback after stamping for HS1, HS2, and HS3 in case of pattern A are shown (Fig.7). HS3 produced lowest variation and springback while HS2 had highest variation and springback for pattern A. It can be seen that increase in variation leads to increase in springback as well.

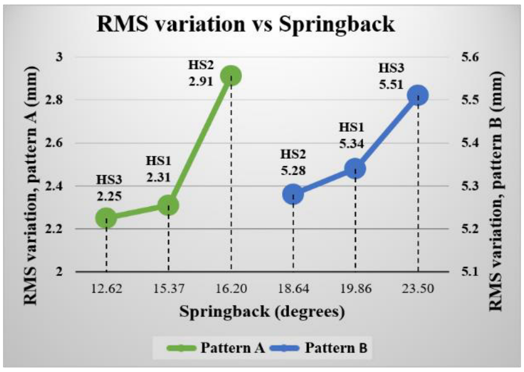


Fig. 7. RMS variation and springback from pattern A and B

The cause for such variation and springback is demonstrated using Fig.8. As the laser heating is carried out in heating areas (HA) from one end of the blank to the other, say from S_1 to S_2, rapid quenching of the already heated region takes place in ambient conditions. That is, a_1 begins to quench as the laser heating approaches b_1, both a_1 and b_1 undergo quenching as heating approaches c_1. HAZ are also formed. The same process repeats for every heat treated area.

In case of HS1 and HS2, when laser heating moves from c_1 to a_2, a_1 will have nearly quenched. In addition, due to wide enough gap between HA_1 and HA_2, heating of a_2 does not affect a_1. Presence of sufficient area of cold bulk material minimizes the effect of stresses generated in both HA_1 and HA_2. In case of HS3, laser heating moves from a_1 to c_1 and then to c_2 as heating of HA_2 begins at c_2. Due to wide enough gap between the HA_1 and HA_2, there is sufficient cold bulk material present. But due to change in sequence, c_2 quenches right after c_1. This change in heating sequence in case of HS3 also changes the sequence of stress formation in the blank. This is different compared to HS1 and HS2 where heating and quenching of c_2 occur much later. Such stress distribution across the blank lowers the variation further in case of HS3. Therefore, HS3 produced lower variation in case of pattern A.

When this heat treated blank is subjected to stamping, the hardened heat treated areas resist deformation. It transfers the stamping forces on the cold bulk material area and they undergo plastic deformation first. Presence of retained austenite in the microstructure further contributes to deformation. This retained austenite transforms to martensite during stamping process as it undergoes plastic deformation. Hence, presence of retained austenite reduces springback. Such characteristics of the selectively laser heat treated boron steel blank can be compared to that of transformation induced plasticity (TRIP) steels [29].

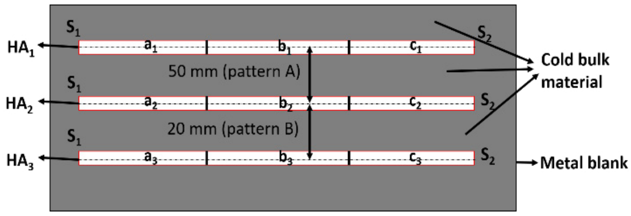


Fig.8. Effect of heating direction sequence and heat treatment pattern

5.2. Heat treatment pattern B

The mean variation at blank level and the corresponding springback after stamping for HS1, HS2, and HS3 in case of pattern B are shown (Fig. 7). HS2 produced lowest variation and springback while HS3 produced higher variation and springback for pattern B. The difference in variation and springback among HS1 and HS2 was relatively low. The trend of increase in variation leading to increase in springback was also seen for pattern B.

Due to smaller pattern dimensions of 20 mm, the total number of heating areas in pattern B is more than doubled. This results in lesser cold bulk material opposing the stresses generated. In case of HS1 and HS2, the mechanism remains the same as explained for heating pattern A. In case of HS3, c_2 is heated right after c_1. As c_1 begins to quench, c_2 undergoes heating. Due to close proximity between HA_1 and HA_2, combined effected of heating c_1, followed by c_2 increases the stress build up in HA_1, HA_2 and the material in between them resulting in higher variation. Heating and quenching process is of importance due to narrow gap, which leads to HS3 producing higher variation than HS1 and HS2. Even though pattern B has more heat treated areas covering large area of the blank similar to that of a furnace heat treatment process, it produces higher variation. Higher springback in pattern B can be attributed to lesser presence of cold bulk material. Delay in deformation due to resistance from the heat treated areas that are higher in number as well as residual stresses results in higher springback.

6. Summary

Three heating direction sequence strategies were tested for two heat treatment patterns. Stresses generated during the laser heat treatment process due to temperature gradient and microstructure transformation contributes to variation at blank level and forms residual stresses. Combined effect of variation, residual stresses, and microstructure affects the subsequent stamping process and springback. Therefore, It is important to supress variation in early stages as it is evident that it propagates to subsequent processes, i.e. from heat treated blank to stamped part. It can also be concluded from the case studies that it is not required to cover larger area of the blank by laser heat treatment. Heat treating only critical areas is sufficient for enhancing formability and functional requirements as highlighted in researches referred earlier. An example of different possibilities is shown (Fig.9).

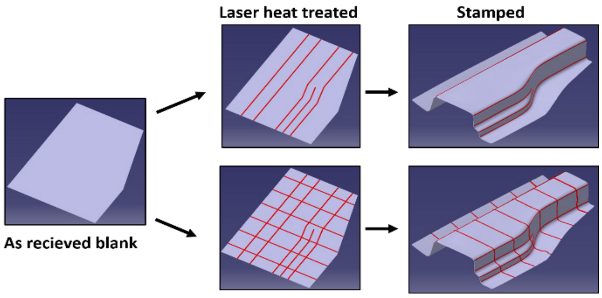


Fig.9. Heat treatment pattern possibilities

Hence, importance towards heating sequence and direction should be given in order to minimize variation and its effects in case of a part subjected to selective laser heat treatment. Right combination of these two are necessary to minimize variation as well as springback. Therefore, for laser parameters similar to the case study performed, choice of a pattern should be made such that sufficient cold bulk material area is available. Residual stresses generated should be accounted for in the concept phase by incorporating them in the variation simulation process. Prediction of residual stresses also facilitates simulating heat treatment pattern concepts for a chosen part design and locating schemes. Allocation of tolerances can then be performed to minimize the effects of variation.

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